Single Spin Superconductivity: Bulk and Junction Effects

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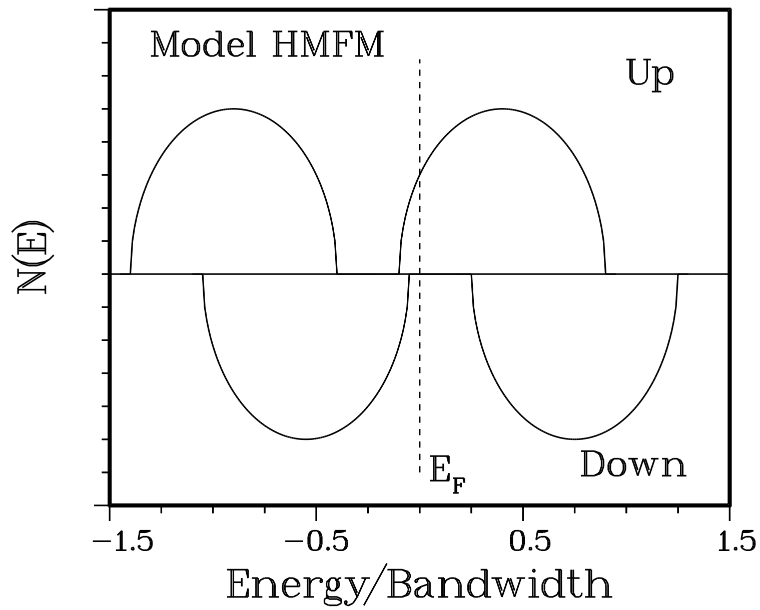
Overview

- **A new kind of superconductivity will occur if a half-metallic antiferromagnet is cooled until it becomes superconducting. This state is called Single Spin Superconductivity.** (W.E.P. PRL 77, 3185 (1996))

- **The properties of SSS differ significantly from singlet, triplet and high T_c superconductivity.**
  - **SSS Cooper pairs consist of 2 spin up electrons.**
  - **Symmetry of the normal phase: $U(1) \times \mathcal{I} \times G$.**
  - **SSS has the minimal symmetry required for superconductivity.**
  - **Time-reversal invariance is broken even in the normal phase.**
  - **The gap function has odd parity and nodes.**

Half-Metallic Ferromagnetism

- **Spin down electrons are insulating.**
- **Spin up electrons are conducting.**
- **The spin moment is an integer (in stoichiometric HM FMs).**

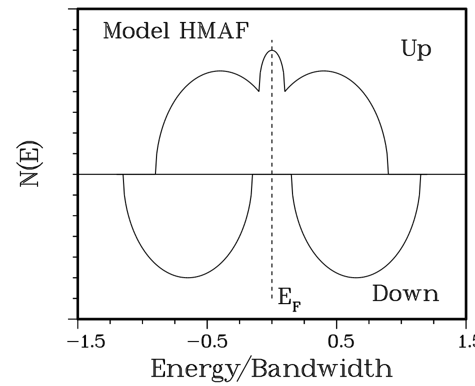


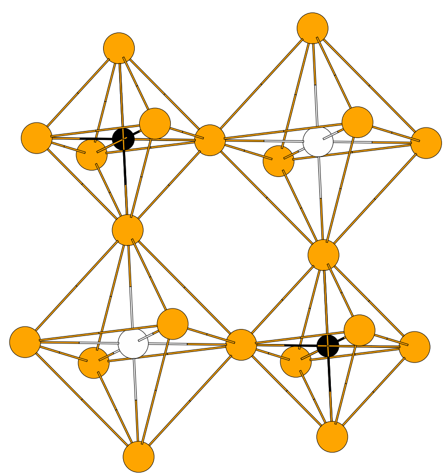
Examples:

- **Heusler Alloys (UNiSn, NiMnSb) (de Groot & Buschow)**
- **Colossal Magnetoresistance Manganates (Pickett & Singh)**
- **CrO_2 (Schwarz)**

Half-Metallic Antiferromagnetism

- **A Half-Metallic Antiferromagnet is half-metallic with zero net spin moment.**
- **No symmetry relates up and down spins.**
- **100% polarized charge transport.**
- **No spin flips allowed.**





Candidates:

- **$V_7MnFe_8Sb_7In$ (van Leuken & de Groot)**
- **La_2VCuO_6, La_2MnVO_6 (Pickett)**

← The double Perovskite La_2VCuO_6
(The La ions are not pictured.)

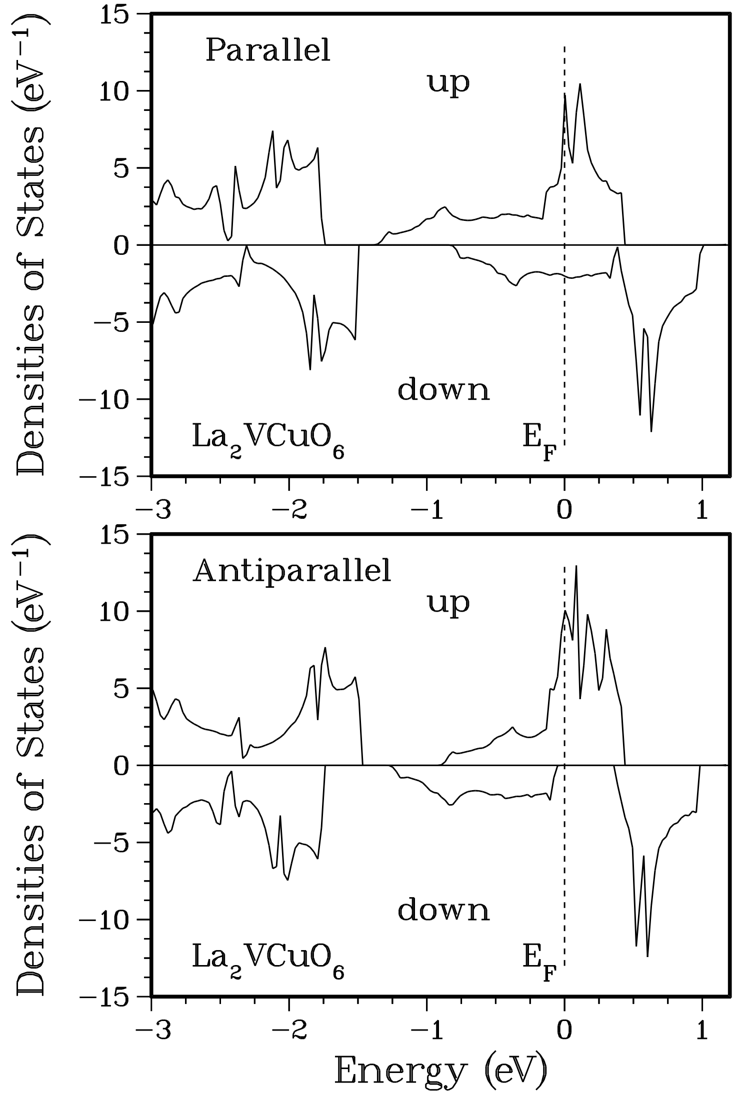
The Density of States for La_2VCuO_6

Ferromagnetic Phase →

$M = 1.38\ \mu_B$/cell

Half-Metallic Anitferromagnetic Phase →

LSDA Prediction (Pickett)



Formulation of SSS

- **At weak coupling, the formalism is very similar to BCS.**
- **Assume 2 spin up electrons in an inversion symmetric Cooper pair.**

The relevant part of the effective Hamiltonian:

$$\mathbf{H}_{\text{pair}} = \sum_{\mathbf{K}} \epsilon_{\vec{\mathbf{k}}} (\mathbf{a}^{\dagger}_{\mathbf{K}} \mathbf{a}_{\mathbf{K}} + \mathbf{a}^{\dagger}_{\mathcal{I}\mathbf{K}} \mathbf{a}_{\mathcal{I}\mathbf{K}}) + \sum_{\mathbf{K}} \sum_{\mathbf{K}'} \mathbf{U}_{\mathbf{K},\mathbf{K}'} (\mathbf{a}_{\mathbf{K}} \mathbf{a}_{\mathcal{I}\mathbf{K}})^{\dagger} (\mathbf{a}_{\mathbf{K}'} \mathbf{a}_{\mathcal{I}\mathbf{K}'}).$$

The gap function:

$$\mathbf{\Delta}_{\mathbf{K}} = \sum_{\mathbf{K}'} \mathbf{U}_{\mathbf{K},\mathbf{K}'} \langle \mathbf{a}_{\mathbf{K}} \mathbf{a}_{\mathcal{I}\mathbf{K}} \rangle.$$

The gap equation (with $\beta = \mathbf{1/kT}$):

$$\mathbf{\Delta}_{\vec{\mathbf{k}}} = -\sum_{\vec{\mathbf{k}}'} \frac{\mathbf{W}_{\vec{\mathbf{k}},\vec{\mathbf{k}}'}}{\mathbf{2E}_{\vec{\mathbf{k}}'}} \mathbf{\Delta}_{\vec{\mathbf{k}}'} \tanh\left(\tfrac{1}{2}\beta \mathbf{E}_{\vec{\mathbf{k}}'}\right).$$

$$\begin{aligned}
\mathbf{W}_{\vec{\mathbf{k}},\vec{\mathbf{k}}'} &= \tfrac{1}{2}\left[\mathbf{V}_{\vec{\mathbf{k}},\vec{\mathbf{k}}'} + \mathbf{V}_{-\vec{\mathbf{k}},-\vec{\mathbf{k}}'} - \mathbf{V}_{\vec{\mathbf{k}},-\vec{\mathbf{k}}'} - \mathbf{V}_{-\vec{\mathbf{k}},\vec{\mathbf{k}}'}\right] \\
&= -|\mathcal{W}| \frac{\vec{\mathbf{k}} \cdot \vec{\mathbf{k}}'}{\mathbf{3k_F^2}} + \cdots
\end{aligned}$$

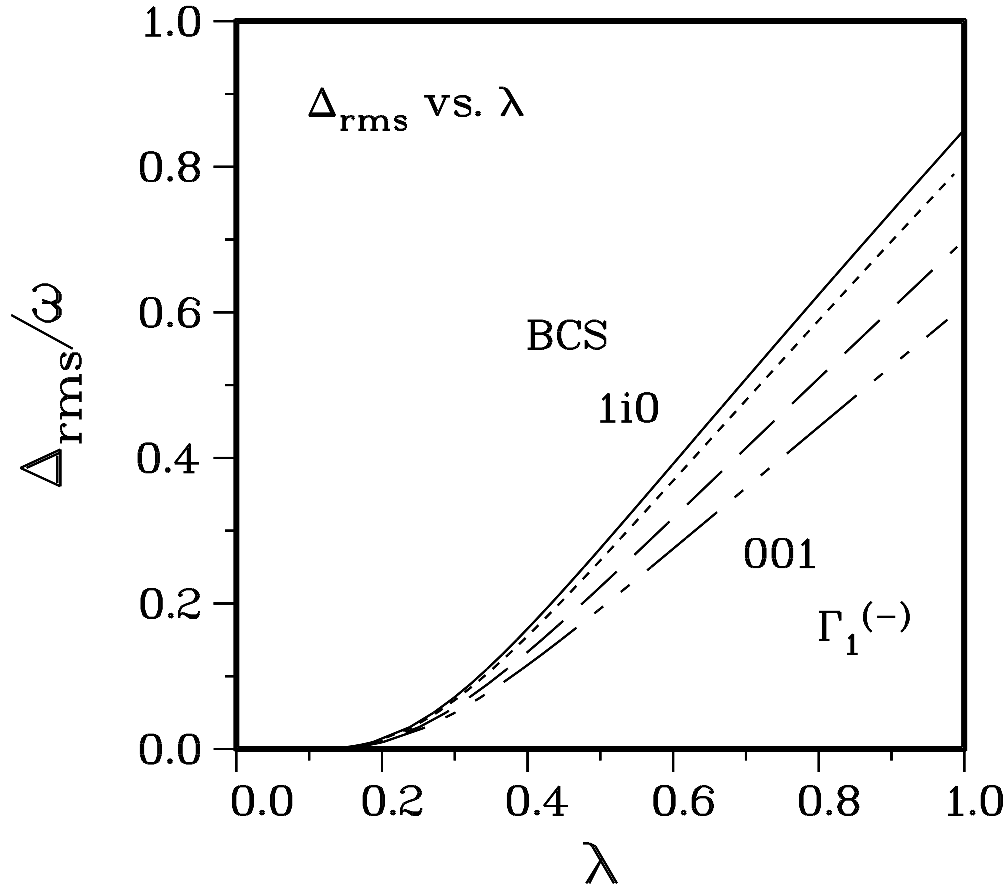
$\boxed{\mathbf{T=0\ SSS\ Gap}}$

$$\mathbf{\Delta_{(0,0,1)} = \sqrt{3}\Delta_{rms} k_z}$$

$$\mathbf{\Delta_{(1,i,0)} = \sqrt{\tfrac{3}{2}}\Delta_{rms}(k_x + i k_y)}$$

$$\lambda_{\mathrm{BCS}} = \mathbf{N(0)V}$$

$$\lambda_{\mathrm{SSS}} = \mathbf{N(0)}|\mathcal{W}|$$



The RMS value of the SSS gap function at $T = 0$ is only slightly reduced at a fixed coupling despite the presence of nodes.

Ginzburg-Landau Theory

- **We have constructed the Ginzburg-Landau free energies for SSS consistent with cubic, hexagonal and tetragonal point groups.**
- **Group theoretic techniques were used to construct the symmetric form of F to all orders in the gap function, $\mathbf{\Delta}$.**

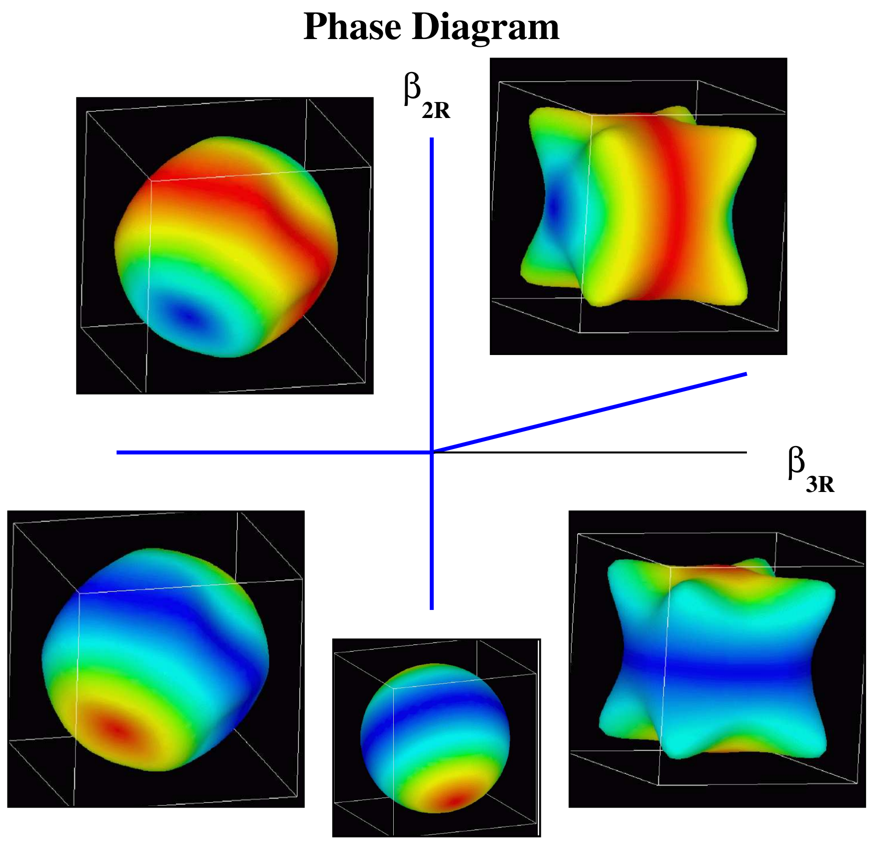
$$\mathbf{\Delta} \propto \mathbf{r}\,\mathbf{e}^{2i\theta}\left[\mathbf{e}^{\mathbf{w}/2}\mathbf{k_x} + \mathbf{e}^{-\mathbf{w}/2}\mathbf{k_y}\right]$$

$$\begin{aligned}\mathbf{F}(\mathbf{\Gamma_5^-}(\mathbf{D_{4h}})) &= \alpha\,\mathbf{r}^2 + \beta_1\,\mathbf{r}^4 + \beta_2\,\mathbf{r}^4\mathbf{sech}^2(\mathcal{R}\mathbf{e}\,\mathbf{w}) + \beta_3\,\mathbf{r}^4\mathbf{cos}(\mathcal{I}\mathbf{m}\,\mathbf{2w})\,\mathbf{sech}^2(\mathcal{R}\mathbf{e}\,\mathbf{w}) \\ &+\gamma_1\,\mathbf{r}^6 + \gamma_2\,\mathbf{r}^6\,\mathbf{sech}^2(\mathcal{R}\mathbf{e}\,\mathbf{w}) + \gamma_3\,\mathbf{r}^6\,\mathbf{cos}(\mathcal{I}\mathbf{m}\,\mathbf{2w})\,\mathbf{sech}^2(\mathcal{R}\mathbf{e}\,\mathbf{w}) \\ &+\gamma_4\,\mathbf{r}^6\,\mathbf{tanh}(\mathcal{R}\mathbf{e}\,\mathbf{w})\,\mathbf{sech}^2(\mathcal{R}\mathbf{e}\,\mathbf{w})\,\mathbf{sin}(\mathcal{I}\mathbf{m}\,\mathbf{2w}) + \cdots\end{aligned}$$

- **We have found the generalized phase diagram in the multidimensional space of Ginzburg-Landau couplings up to sixth order in $\mathbf{\Delta}$.**

Generalized Phase Diagram

The illustration shows the Ginzburg-Landau phase diagram for cubic SSS. There are four generic phases, and one that exists only on the negative β_{2R} axis. Each phase is depicted by a plot of the squared magnitude of the gap function, $|\Delta|^2$. Blue regions are near zero magnitude, while red is near the maximum.



Experimental Tests

Half-Metallic Antiferromagnetism:

- **Non-Korringa behavior in NMR (Pickett)**
  - **The longitudinal relaxation rate should vanish.**
  - **The Knight shift should be small.**
- **Vanishing Spin Susceptibility (Pickett)**
- **Resistivity and Magnetic Susceptibility (Fujii, et al)**
- **Spin-Polarized, Angle-Resolved Positron Annihilation (Mijnarends, et al)**
- **Spin-Polarized Photoemission (Schwarz)**

Single Spin Superconductivity:

- **Power-Law Scaling of Thermodynamic Quantites with T.**
- **Possibility of Multiple Superconducting Phases.**
- **Spin-Polarized Superconducting DOS via HM-SSS Junction.**
- **Dependence of Properties on Direction of Applied B Field.**
- **Absence of Tunneling in High-Quality BCS-SSS Junctions.**

SSS Junction Effects

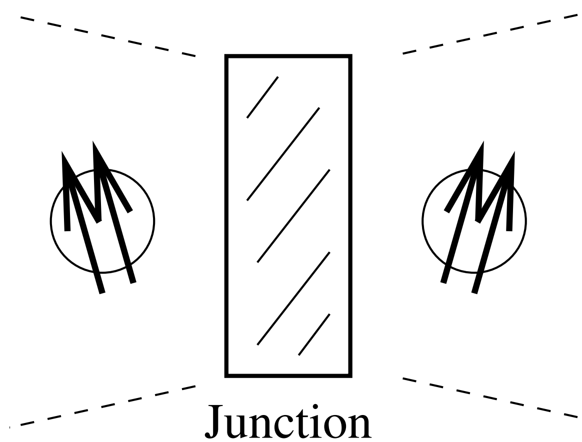
The tunneling Hamiltonian depends on the orientation θ of the spin axes on the two sides of the junction:

$$\mathbf{H_T} = \sum_{\vec{\mathbf{k}},\vec{\mathbf{p}}} \left(\mathbf{T}_{\vec{\mathbf{k}}\vec{\mathbf{p}}}\, \mathbf{d}^{\frac{1}{2}}_{\frac{1}{2},\frac{1}{2}}(\theta)\, \mathbf{c}^{\dagger}_{\vec{\mathbf{k}}} \mathbf{c}_{\vec{\mathbf{p}}} + \mathrm{h.c.} \right)$$

The resulting DC Josephson current for tunneling between two regions of $\hat{\mathbf{d}}$=(1,i,0) of T_{1u} cubic symmetry at an angle φ and with a phase difference ϕ is

$$\mathbf{I_J^{V=0}} = \frac{\sigma_0}{\mathbf{e}} \frac{\pi \boldsymbol{\Delta}}{\mathbf{4}} \left(\mathbf{cos}(\theta) + \mathbf{1} \right) \mathbf{sin}(\phi)\, \mathbf{cos}(\varphi)\, \mathbf{tanh}\left(\frac{\beta}{\mathbf{2}} \boldsymbol{\Delta} \right)$$

where the maximal normal conductance is given by $\sigma_0 = \mathbf{2}\pi \mathbf{e^2 N_L N_R} |\mathbf{T_0}|^{\mathbf{2}}$.



Summary

- **Pairing interaction in HM AFMs leads to Single Spin Superconductivity.**
- **The fundamental characteristic is that both electrons have spin up in the Cooper pairs and there are no compensating down Cooper pairs.**
- **Specific Predictions:**
  - **The gap function must have nodes—thermodynamic quantities scale as a power of the temperature.**
  - **Spin polarized Josephson effect.**
  - **SSS is unlikely to be high T_c because increasing T degrades the underlying HM AFM normal state (spin fluctuations).**
  - **In a weakly coupled system with cubic symmetry, the leading candidate for the ground state gap function is $\boldsymbol{\Delta}_{(1,\mathrm{i},0)} = \sqrt{\frac{3}{2}}\boldsymbol{\Delta}_{\mathrm{rms}}(\mathbf{k_x} + \mathbf{i}\mathbf{k_y})$**